arXiv:0811.3981v1 [astro-ph] 24 Nov 2008

Comm. in Asteroseismology
Contribution to the Proceedings of the 38^{th} LIAC/HELAS-ESTA/BAG, 2008

Rotational mixing in tidally locked massive main sequence binaries

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Abstract

One of the main uncertainties in evolutionary calculations of massive stars is the efficiency of internal mixing. It changes the chemical profile inside the star and can therefore affect the structure and further evolution.

We demonstrate that eclipsing binaries, in which the tides synchronize the rotation period of the stars and the orbital period, constitute a potentially strong test for the efficiency of rotational mixing. We present detailed stellar evolutionary models of massive binaries assuming the composition of the Small Magellanic Cloud. In these models we find enhancements in the surface nitrogen abundance of up to 0.6 dex.

Introduction

The inclusion of rotation into stellar evolution models has been shown to be very successful in explaining various observed characteristics of stars (see Maeder & Meynet 2000, for a review). It can have a large effect on the internal distribution of elements, as it leads to instabilities in the star, resulting in internal mixing.

The two most important mixing processes induced by rotation are *Eddington-Sweet circulations*, which consist of large scale meridional currents originating from a thermal imbalance between pole and equator in rotating stars (von Zeipel 1924; Eddington 1925, 1926; Vogt 1925) and *shear mixing*, which results from eddies formed between two layers of the star rotating at different angular velocities.

Near the center of a massive main sequence star hydrogen is converted into helium, and carbon and oxygen into nitrogen. Rotational mixing can bring this

processed material to the surface, where it can be observed in the stellar spectra. Therefore rotation has been proposed as an explanation for the enhanced nitrogen abundances observed in a fraction of massive early type stars (e.g. Walborn 1976; Maeder & Meynet 2000; Heger & Langer 2000).

Although the effects of rotation on stellar evolution have been studied by various authors, we are still left with many questions. An essential question concerns the efficiency of rotational mixing. Attempts to constrain it have remained inconclusive due to limited sample sizes and/or a strong bias towards stars with small projected rotational velocities (e.g. Gies & Lambert 1992; Fliegner et al. 1996; Daflon et al. 2001; Venn et al. 2002; Korn et al. 2002; Huang & Gies 2006; Mendel et al. 2006).

The recent VLT-flames survey of massive stars (Evans et al. 2005) provided for the first time a large sample of massive stars covering a wide range of projected rotational velocities with accurate abundance determinations (Hunter et al. 2008). Brott et al (2008, this Vol.) demonstrated that the properties of the VLT-flames sample cannot be reproduced by simulations of a population of rotating single stars. This raises the question whether other processes, beside rotational mixing, play an important role in explaining helium and nitrogen enhancements of massive main sequence stars. For example, the observed enhancements could also be explained by binary interactions (Langer et al. 2008). In this case a downward revision of efficiency of the rotational mixing in single stars might be required.

Clearly, a strong and conclusive observational test for the efficiency of rotational mixing is needed. In this contribution we propose to use detached eclipsing binaries for this purpose.

Eclipsing binaries as laboratories for rotational mixing

Eclipsing binaries have frequently been used to test stellar evolution models as they provided the only method (until the development of asteroseismological techniques) for accurate determinations of stellar masses masses, radii and effective temperatures. Even beyond our own Galaxy, in the Magellanic Clouds, masses of O and early B stars have been determined with accuracies of 10% (Hilditch et al. 2005). Rotational mixing is more important in more massive stars (e.g. Heger et al. 2000). Therefore, it is very useful to know the stellar mass for quantitative testing of the efficiency of rotational mixing: it enables a direct comparison with a corresponding stellar evolution model with the proper mass.

In close binaries, with orbital periods ($P_{\rm orbit}$) less than a few days, the tides are so strong that the stars rotate synchronously with the orbital period: $P_{\rm spin} = P_{\rm orbit}$. With the stellar radii known from eclipse measurements, this

enables us to determine the rotation rate directly from the orbital period. This is an important advantage of using binaries for testing rotational mixing with respect to single stars, for which fitting of spectral lines allows only for the determination of $v \sin i$, where v is the rotational velocity at the equator. The inclination i of the rotation axis is generally not known.

Here, we propose to use detached eclipsing binaries consisting of two main sequence stars residing within their Roche lobes. Detailed calculations of binary evolution show that if one of the stars fills its Roche lobe during the main sequence, it does not detach again before hydrogen is exhausted in the core, except maybe for a very short thermal timescale (Wellstein et al. 2001; De Mink et al. 2007). If we turn the argument around we find that, in a binary with two detached main sequence stars, we can safely exclude the occurrence of mass transfer since the onset of core H burning. The stars have lived their lives similar to rotating single stars. This is a third major advantage of using eclipsing binaries with respect to single stars. A fast rotating single star may in contrast be the result of a merger of two stars in a former binary. Moreover an apparently single star may have been affected by mass transfer, while its companion may be very hard to detect, being a faint low mass star in a wide orbit.

To test rotational mixing we need determinations of the surface abundances. If the spectra of a binary are of high quality, one can determine the surface abundances, as is done for single stars, after disentangling the composite spectra (e.g. Leushin 1988; Pavlovski & Hensberge 2005; Rauw et al. 2005). In the remainder of this paper we discuss what type of binaries are suitable for testing rotational mixing.

Stellar evolution code

To investigate to what extent the surface abundances of close detached binaries are affected by rotational mixing we model their evolution using a detailed 1D stellar evolution code, described by Yoon et al. (2006), which includes the effects of rotation on the stellar structure, the transport of angular momentum and chemical species via rotationally induced hydrodynamic instabilities (Heger et al. 2000) and magnetic torques (Spruit 2002; Heger et al. 2005). Brott et al. (2008, this Vol.) calibrated the efficiency of mixing processes in single star models using the data from the VLT-flames survey (Hunter et al. 2008).

Tidal interaction is implemented as described in Detmers et al. (2008) using the timescale for synchronization given by Zahn (1977, eq. 6.1). The tides act on the outer layers of the star. Angular momentum is redistributed in the stellar interior by magnetic coupling and rotational instabilities. We note that the binary systems modeled here are so tight that the stars are synchronized

throughout their main sequence evolution.

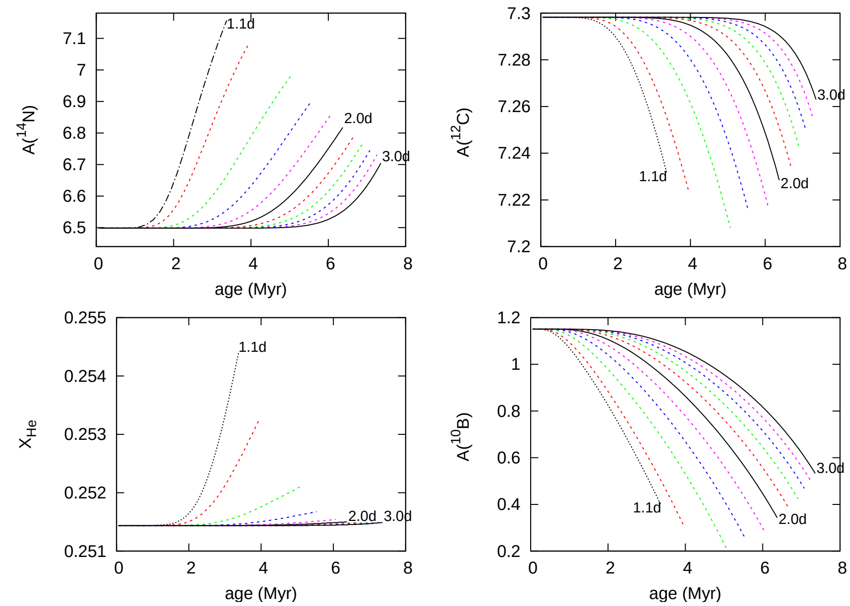

Figure 1: Surface abundances of nitrogen (^{14}N), carbon (^{12}C), boron (^{10}B) and the mass fraction of helium at the surface versus time for a 20 $\mathrm{M}_\odot$ star with a 15 $\mathrm{M}_\odot$ close companion. Note the different vertical scales. The abundance of an element X is given in the conventional units: $A(\mathrm{X}) = \log_{10}(n_\mathrm{X}/n_\mathrm{H}) + 12$, where n_X and n_H refer to the number fractions. The different lines show the evolution assuming different initial orbital period, varying between 1.1 and 3 days. The tracks are plotted from the onset of central H burning until the onset of Roche lobe overflow.

Results

With the Small Magellanic Cloud (SMC) sample of Hilditch et al. (2005) in mind, which contains 21 detached systems[1] with orbital periods of a few days and masses of the primary component up to 20 $\mathrm{M}_\odot$, we chose to model the following binary systems. For the mass of the primary component we adopt 20 $\mathrm{M}_\odot$, for the secondary component 15 $\mathrm{M}_\odot$ and we adopt initial orbital

[1]Possibly only 20 systems are detached. For two of the systems an alternative semi-detached solution. For one of these systems a comparison to binary evolution models including the effects of mass transfer showed that the semi-detached solution was more consistent than the detached solution (De Mink et al. 2007).

periods of up to three days. We assume a composition representative of the small Magellanic cloud, which is relatively metal-poor and has a high carbon to nitrogen ratio. The evolution is followed from the onset of central hydrogen burning at zero age until the primary star fills its Roche lobe.

In all computed models the tides are efficient enough to keep both stars in synchronous rotation with the orbit. The shorter the orbital period, the faster the rotation of the stars, the more efficient rotational mixing, the faster the surface abundances change with time. On the other hand, the systems with short orbital periods are tighter and therefore the stars will fill their Roche lobe at an earlier stage, leaving less time to modify their surface abundances. These effects are illustrated in Fig. 1.

Nitrogen is produced in the core and in the layers just above, as carbon and oxygen are consumed. Due to rotational mixing the nitrogen surface abundance increases and the carbon abundance decreases accordingly (see Fig. 1). Helium is produced deeper inside the star on a much longer timescale (the nuclear timescale). Some helium can be mixed up, but the helium surface enhancements achieved in our models are very small (less than 1%). Another element that acts as a tracer of rotational mixing is boron. This element can only survive in the coolest outermost layers of the star. Rotational mixing will bring it to hotter layers where it is destroyed. It is one of the elements most sensitive to rotational mixing. It is, however, hard to observe due to its low abundance, especially in the metal poor SMC. The increase in the nitrogen abundance in our models is up to three times larger than the typical error bar for surface abundance measurements in the VLT-flames survey (0.2 dex). Nitrogen may therefore be the most suitable element to test rotational mixing.

Conclusion

We have argued that eclipsing binaries can provide a potentially stringent test for the efficiency of rotational mixing in massive stars. The stellar parameters and rotation rate can be accurately determined enabling direct comparison to stellar evolution models. Therefore even one well determined system could be used as a test case. By performing detailed evolutionary calculations of close massive binaries, we show that (with currently assumed rotational mixing efficiencies) we expect nitrogen enhancements of up to 0.6 dex for binaries such as those in the sample of Hilditch et al. (2005).

At present, it is not clear whether the presence a of binary companion can lead to extra mixing, on top of the rotationally induced mixing. If so, our proposed test would still constrain the efficiency of rotational mixing in single stars by providing an upper limit to this quantity. This will be discussed in a forthcoming paper.

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